SIGNALS FOR TAU NEUTRINO INTERACTIONS

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Ways of detecting tau neutrinos emerging from a beam dump are studied. Key signatures are elaborated and contrasted with background arising from muon and electron neutrino interactions. Expected event rates are given for various neutrino spectra.

I would like to discuss the possibility of detecting tau neutrino interactions in future beam dump experiments. My report is based on studies carried out in collaboration with Robert Shrock and Jack Smith.[1)]

1. Introduction

The existence of a heavy charged lepton, τ^-,[2)] with mass 1.785 ±0.010 GeV has now been well established[2)] in e^+e^- annihilation experiments carried out at SPEAR and DORIS. On the other hand, the corresponding existence of its own associated neutrino, ν_τ, has mainly been inferred[2)] from the charged lepton momentum spectrum best described by the 3-body decay modes $\tau^- \to \nu_\tau e^- \bar{\nu}_e$ and $\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu$. Postulating the existence of such a neutrino, upper limits have been placed on its mass, the latest[3)] being $m_\nu \leq 250$ MeV (95% c.l.). The charged e^- (or μ^-) momentum spectrum strongly favors a V-A interaction at the τ-ν vertex with a weak interaction coupling strength $g^2_{\tau\nu} \geq 0.12\ g^2_{\mu\nu}$ inferred from an upper experimental limit for the τ lifetime.[2)] With regard to the leptonic nature of the ν_τ, it should be noted the possibility that ν_τ is identical to ν_μ or $\bar{\nu}_\mu$ has been ruled out by the Columbia-Brookhaven neutrino group[4)] while data from the SLAC-LBL group[5)] at SPEAR eliminated the possibility that τ^- is a paralepton with $\nu_\tau = \bar{\nu}_e$. Whether ν_τ is a new sequential neutrino coupled only to τ^- or whether $\nu_\tau = \nu_e$ remains an open question.

Theoretically it is most appealing, given the success[6)] of the standard Weinberg-Salam SU(2)×U(1) gauge model,[7)] to place the ν_τ and τ leptons simply into a new doublet family.[8)] Other possibilities such as assigning the τ to a triplet representation with $\nu_\tau \equiv \nu_e$, either in the $SU(2)_L \times U(1)$ gauge group or in an expanded $SU(3)_L \times U(1)$ gauge group, encounter difficulties connected with mixing angles and universality.[9)] In any event, one would like to isolate ν_τ interactions and to confirm that the tau neutrino is a new entity and not, for example, the electron neutrino. In the remainder of my report, I shall assume the extended Kobayashi-Maskawa SU(2)×U(1) gauge model[8)] is correct and make predictions which test the ν_τ and τ assignments in this model.

TYPING AREA STARTS HERE

2. ν_τ Sources and Flux Calculations

Among the more important tau neutrino sources are the following:

(a) Electromagnetic Production of Tau Pairs

Both the Drell-Yan and the Bethe-Heitler mechanisms yield cross sections which are much too small,[10),11)] i.e., of the order of $10^{-36}cm^2$ and $10^{-37}cm^2$, respectively.

(b) b Quark Decays

Barger and Phillips[13)] have suggested hadronic production of b quark-flavored mesons folllowed by a $b\to\tau\nu$ decay as a possible source of tau neutrinos, but a realistic estimate yields $\sigma(M_b\bar{M}_b)B(b\to\tau\nu_\tau) \gtrsim 10^{-34}cm^2$, which is also very small.

(c) D and F Charmed Meson Decays

The D^+ pseudoscalar meson can undergo the decay mode[13)] $D^+\to \tau^+\nu_\tau$, but this decay is Cabibbo suppressed and has a Q-value of only ≈86 MeV. The corresponding F^+ meson decay,[13)] on the other hand, is Cabibbo favored and has a larger Q-value of ≈250 MeV. Assuming SU(4) symmetry so $f_F=f_D=f_K=f_\pi$, one finds branching ratios[14)] of $B(D\to\tau\nu_\tau)\approx 0.02\%$ and $B(F\to\tau\nu_\tau)\approx 3\%$. The hadronic production cross section for $D\bar{D}$ pairs has been measured in beam dump experiments at the SPS by the ABCLOS, CDHS and GGM groups[15)] and by the Caltech-Stanford group[16)] at Fermilab and found to be of the order of 100μb. A crude estimate of $F\bar{F}$ production can be obtained by scaling[17)] $\sigma(D\bar{D})$ by the ratio $\sigma(K\bar{K})/\sigma(\pi\pi)$ with a result of order 10μb. Hence one obtains $\sigma(D\bar{D})B(D\to\tau\nu_\tau)\approx$ 0.02μb and $\sigma(F\bar{F})B(F\to\tau\nu_\tau)\approx 0.3\mu b$.

The main source of tau neutrinos is thus the decay of F charmed mesons which are pair produced by the primary proton reaction

$$p + N \to F^+ + F^- + X \quad . \qquad (1)$$

Since the cross section is low, one must resort to a beam dump experiment in order to suppress the copious flux of ordinary $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ neutrinos from π and K decays in favor of neutrinos arising from the decay of short-lived charmed particles. Both primary and secondary $\overset{(-)}{\nu}_\tau$'s arise in the F decays

$$F^\pm \to \tau^\pm + \overset{(-)}{\nu}_\tau \qquad (2a)$$

$$\tau^\pm \to \overset{(-)}{\nu}_\tau + \text{anything} \qquad (2b)$$

yielding identical flux spectra for the ν_τ and $\bar{\nu}_\tau$ beams.

If one assumes complete absorption of the π and K mesons, one can give a crude estimate of the ν_τ flux relative to the ν_μ flux from D decay:

$$\frac{N(\nu_\tau)}{N(\nu_\mu)} = 2\frac{\sigma(F\bar{F})}{\sigma(D\bar{D})}\,\frac{B(F^{+}\to\tau^{+}\nu_\tau)}{B(D^{+}\to\tau^{+}\nu_\tau)}$$

$$\simeq 2\left(\frac{10\mu b}{100\mu b}\right)\frac{0.03}{0.10} = 0.06 \qquad (3)$$

where the factor of 2 takes into account both the primary and secondary sources. A more accurate calculation can be made based on the observation that inclusive hadron production, $p+N\to H+\ldots$, is well described by a phenomenological formula[18] given by Bourquin and Gaillard and Hinchliffe and Llewellyn Smith for any mesons (π, ρ, J/ψ, ...) over the entire p_T range. Mori[19] has applied this formula to D and F meson production and used a Monte Carlo calculation to fold in the decays with the results shown in Fig. 1 for a 400 GeV proton beam incident on a copper dump 250 cm upstream of a detector subtending a half angle of 0-2 mrad. The two-component nature of the ν_τ flux curve is due to the soft $\overset{(-)}{\nu}_\tau$'s from the primary $F\to\tau\nu_\tau$ decays and the harder $\overset{(-)}{\nu}_\tau$'s from the secondary τ decays.

It should be emphasized that the ν_τ flux calculation[19] is conservative in that $B(F\to\tau\nu_\tau)\simeq 3\%$ based on $f_F=f_K$ is probably low; $\sigma(F\bar{F})/\sigma(D\bar{D})$ may actually be closer to 0.5 rather than 0.1 since the F and D masses are more nearly equal than the K and π masses; the $F\bar{F}^* + F^*\bar{F}$ and $F^*\bar{F}^*$ production channels were neglected; and only 68% of the τ decays were taken into account in Mori's calculation.[19] Since the p_T distribution is narrow for π's and K's and broad for D's and F's, one can missteer the beam to suppress further the neutrinos from π's and K's which are not absorbed, but one cannot enhance $\overset{(-)}{\nu}_\tau$'s from F decays vis. a vis. $\overset{(-)}{\nu}_\mu$'s and $\overset{(-)}{\nu}_e$'s from D decays. Missteering the beam also has the disadvantage of reducing the high energy part of the ν_τ spectrum.

3. Event Rates and Signatures

Some of the $\overset{(-)}{\nu}_\tau$'s produced in the dump will interact in the downstream detector. Interactions of interest include the charged current interactions

$$\nu_\tau + N \to \tau^- + X$$

$$\hookrightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu \qquad (4c)$$

$$\hookrightarrow \nu_\tau + e^- + \bar{\nu}_e \qquad (4b)$$

$$\hookrightarrow \nu_\tau + \text{hadrons} \qquad (4c)$$

as well as the neutral current interaction

$$\nu_\tau + N \to \nu_\tau + X \quad . \qquad (5)$$

Since the tau mass cannot be neglected, the charged current cross section is expressed in terms of 5 structure functions which one would ultimately like to determine.[20] If we simply adopt the naive quark parton model predictions that $F_2=2xF_1=xF_3=xF_5$ and $F_4=0$, and assume that the neutral-current to charged-current ratios, NC/CC, are 0.29 and 0.35 for neutrinos and antineutrinos, respectively, we find the following event rates[1] given in Table 1 for the Mori flux spectrum with the reaction $\nu_\mu+N\to\mu^-+X$ normalized to 10,000 events.[21] It is clear from the table that the $\overset{(-)}{\nu}_\tau$ signals comprise only about 1% of the entire sample of events, so clearly one must devise critical tests which can suppress the large background.

Table 1. Relative event rates (with no cuts) applicable to a 400 GeV primary proton beam with a copper dump and a detector downstream subtending a half angle of 0 to 2 mrad.

Reaction	No. of Events
$\nu_\mu\to\mu^-$	10,000
$\nu_e\to e^-$	7,200
$\nu_\tau\to\tau^-\to\mu^-$	40
$\nu_\tau\to\tau^-\to e^-$	40
$\nu_\tau\to\tau^-\to\nu_\tau$	120
$\nu_\mu\to\nu_\mu$, $\nu_e\to\nu_e$, $\nu_\tau\to\nu_\tau$	5,100
$\bar\nu_\mu\to\bar\nu_\mu$, $\bar\nu_e\to\bar\nu_e$, $\bar\nu_\tau\to\bar\nu_\tau$	2,300
$\nu_\tau\to\tau^+\to\bar\nu_\tau$	45
$\bar\nu_\mu\to\mu^+$	3,400
$\bar\nu_e\to e^+$	3,000
$\bar\nu_\tau\to\tau^+\to\mu^+$	15
$\bar\nu_\tau\to\tau^+\to e^+$	15

3.1. Anomalous NC/CC Ratio Test

The neutral current reaction (5) yielding $\nu_\tau\to\nu_\tau$ and the charged current reaction (4c) yielding $\nu_\tau\to\tau\to\nu_\tau$, as well as their $\bar\nu_\tau$ counterparts, will enhance the apparent NC/CC ratio over that prevailing in a pure $\overset{(-)}{\nu}_\mu$ beam.[22]

Since the $\overset{(-)}{\nu}_\tau$ flux from Fig. 1 is about 30 times smaller than that of the ν_μ and $\overset{(-)}{\nu}_\mu$ fluxes, the apparent increase in the NC/CC ratio is small: with perfect electron identification, we find[1] $\sigma(\overset{(-)}{\nu}\to\overset{(-)}{\nu})/\sigma(\nu\to\mu^-)=0.72\to0.75$ while the increase is from $1.74\to1.75$ with no electron identification. Since the uncertainty in the neutrino flux is greater than this, one cannot use this test as an accurate indication of ν_τ interactions.

3.2. Double Shower Test

Reaction (4c) will lead to events with two apparent hadron showers present. One could attempt to identify such events,[23] but our Monte Carlo studies show[1] that the typical opening angle is 8°–10° between the two shower directions whereas the spread in one hadron shower is 20°–30°; moreover, typically only 1-3 hadrons originate from the tau decay, so this test also will generally not be successful in identifying $\overset{(-)}{\nu}_\tau$ events.

3.3. Muon Trigger Test

The apparent charged current reaction (3a) with one muon and two neutrinos, however, appears to be a reliable indicator of a $\overset{(-)}{\nu}_\tau$ interaction as will be made clear.[1] The muon serves to tag the interaction as being neutrino- or antineutrino-induced, while the two neutrinos carry off momentum which generally results in a sizable imbalance in the momentum measured perpendicular to the beam direction, $p_\perp$, or transverse to the apparent production plane, p_T. The azimuthal opening angle between the muon and (missing) neutrino pair in a plane perpendicular to the beam direction is peaked toward 0°, while the corresponding angles between the muon and hadron spray or between the neutrino pair and hadron spray are peaked dramatically toward 180°. These features are shown in Fig. 2 and can be understood by noting that the tau lepton and hadron spray are emitted on opposite sides of the beam direction and that the decay leptons tend to follow roughly the parent τ direction.

The muon trigger test then consists of the following steps.

(a) Trigger on single $\mu^\mp$ events and look for missing momentum perpendicular to the beam direction.

(b) Impose a cut, for example, of $(p_\perp)_{missing} > 1$ GeV/c to eliminate most of the background arising from ordinary mismeasured $\overset{(-)}{\nu}_\mu$ charged current events while reducing the ν_τ signal by only about 50%.

(c) Check the azimuthal opening angle distributions. Since $(p_\perp)_{missing}$ is strongly correlated with the azimuthal opening angle, by making the $(p_\perp)_{missing} >$ 1 GeV/c cut, one finds the $\Delta\phi_{mH}$ angular distribution is even more dramatically peaked toward 180° with $\Delta\phi_{mH} > 120°$; $\Delta\phi_{\mu H} > 90°$ and is strongly peaked at 180°; while $\Delta\phi_{\mu m} > 90°$ and has a maximum at 0°. These features are illustrated in Fig. 3.

(d) Check the apparent x and y distributions. The x_{vis} distribution determined by the visible energy and momentum transfer is sharply peaked toward zero, while the y_{vis} distributions for the ν_τ and $\bar{\nu}_\tau$ reactions are dramatically shifted toward high y as also shown in Fig. 3. These distributions serve as additional checks[24] that $\overset{(-)}{\nu}_\tau$ interactions are the primary source of the events surviving the $(p_\perp)_{missing}$ cut.

Until the present time no counter experiments were able to perform the $(p_\perp)_{missing}$ test since none could measure with reasonable accuracy the direction of the hadronic spray. New detectors which have the capability to measure the direction of the hadronic spray have been or are being built by the CERN-Hamburg-Amsterdam-Rome-Moscow, Michigan-Wisconsin-Ohio State, and FNAL-MIT-MSU-NIU collaborations.[25)-27)] It is estimated that these detectors may be able to measure the hadronic spray direction sufficiently well to determine $(p_\perp)_{missing}$ to an accuracy of $\approx \pm 0.5$ GeV/c. Hence the tests we proposed above are feasible.

4. Expected Backgrounds

The most likely (but not serious) backgrounds that will be encountered are the following.[1)] Mismeasured $\nu_\mu \to \mu^-$ events which survive the $(p_\perp)_{missing}$ cut will yield a flat to slightly forward peaked $\Delta\phi_{mH}$ distribution which is to be contrasted with the sharply peaked backward $\Delta\phi_{mH}$ signal from the ν_τ-induced events. Other sources of background include ordinary neutral current events with a π or K decay into a muon which can be eliminated by a suitable muon energy cut; neutral current induced charmed pair production followed by one semileptonic decay, but the cross section times branching ratio is negligibly small; $\overset{(-)}{\nu}_\mu$-induced single charm production with decay of the charmed particle into the electron mode and the electron shower misidentified as part of the hadron shower; and $\overset{(-)}{\nu}_e$-induced single charm production with decay of the charmed particle into the muon mode, again with the electron shower misidentified as part of the hadron shower. Distributions for the latter two backgrounds are given in Fig. 4a,b and 4c,d, respectively. The ν_μ-induced single charm signals are quite distinct from the ν_τ signals, while the $\bar{\nu}_e$-induced single charm signals are more nearly identical to the ν_τ signals. In general, however, a fair fraction of events involving electron showers can be identified as such and the small fraction of these background events surviving the $(p_\perp)_{missing} > 1$ GeV/c cut renders both single charm production backgrounds harmless.

5. New Signal Interpretation

I have argued that the tests proposed will separate a ν_τ signal from ordinary ν_μ- and ν_e-induced background. If the desired signal is detected, one must still rule out other possible interpretations. Yet another sequential neutrino ν_λ, where λ^- is a new more massive lepton than the tau, can be eliminated since the production rate would be suppressed in the beam dump and the interaction rate suppressed in the detector, thus yielding a negligible signal. Massive electron-type heavy lepton production by the ν_e beam will also yield a negligible signal unless the mass of the heavy electron is close to the present experimental lower limit of 4 GeV. One can expect that this mass limit will be raised in the near future at both the PETRA and PEP storage rings.

Finally, one would like to conclude that ν_τ is not identically equal to ν_e. This requires that we distinguish reaction (4a) from

$$\nu_e + N \to \tau^- + X, \qquad \tau^- \to \nu_e + \mu^- + \bar{\nu}_\mu \quad . \tag{6}$$

The latter reaction would occur at the level of $\geq 0.12(2/3)\times(0.19)\times$(event rate for $\nu_e \to e^-$) ≥ 110 events compared to 40 predicted events for (4a); where the factors 0.12, 2/3 and 0.19 correspond to the present lower limit of the $\nu \to \tau$ coupling, a threshold suppression factor, and the tau branching ratio into the muon mode. In other words, if the tau is ν_e-induced, one would expect that more tau events will be observed in the detector than are predicted for a sequential ν_τ beam. In order to rule out this possibility, one must accurately determine the $F\bar{F}$ production cross section and the $F \to \tau\nu_\tau$ branching ratio. A distinct, but relatively small τ signal in the counter detector would favor a sequential ν_τ interpretation for the origin of the selected events.

6. Summary

I have explained that a ν_τ flux can be produced in a suitable beam dump exposure, that a small fraction of the neutrino events detected will be of the type (4a) $\nu_\tau \to \tau^- \to \mu^-$ if the extended Kobayashi-Maskawa $SU(2)\times U(1)$ gauge model[8] is correct, that a cut on $(p_\perp)_{missing} > 1$ GeV/c can eliminate most of the background and that the azimuthal angle and y_{vis} distributions have characteristic signatures which can be exploited to isolate the ν_τ events. No serious background surviving the $(p_\perp)_{missing} > 1$ GeV/c cut fakes the $\Delta\phi_{mH}$ signal. Accurate knowledge of the $F\bar{F}$ strong interaction production cross section and the $F \to \tau\nu_\tau$ branching ratio will enable one to decide the issue whether ν_τ is a sequential neutrino or whether $\nu_\tau = \nu_e$.

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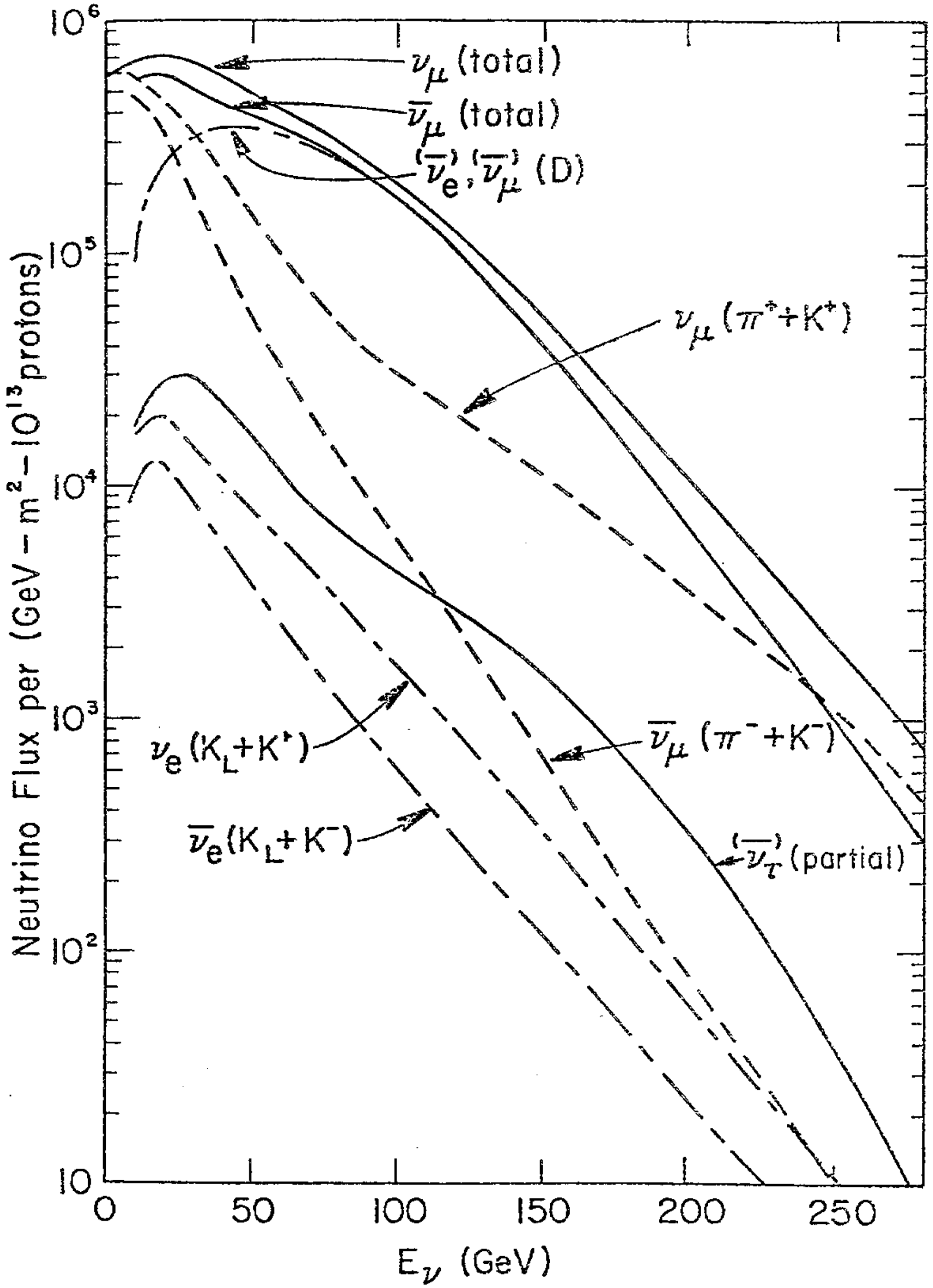

Fig. 1. Neutrino and antineutrino fluxes for 400 GeV proton interactions in a copper beam dump for a detector 250m downstream subtending an angular spread of 0 to 2 mrad.

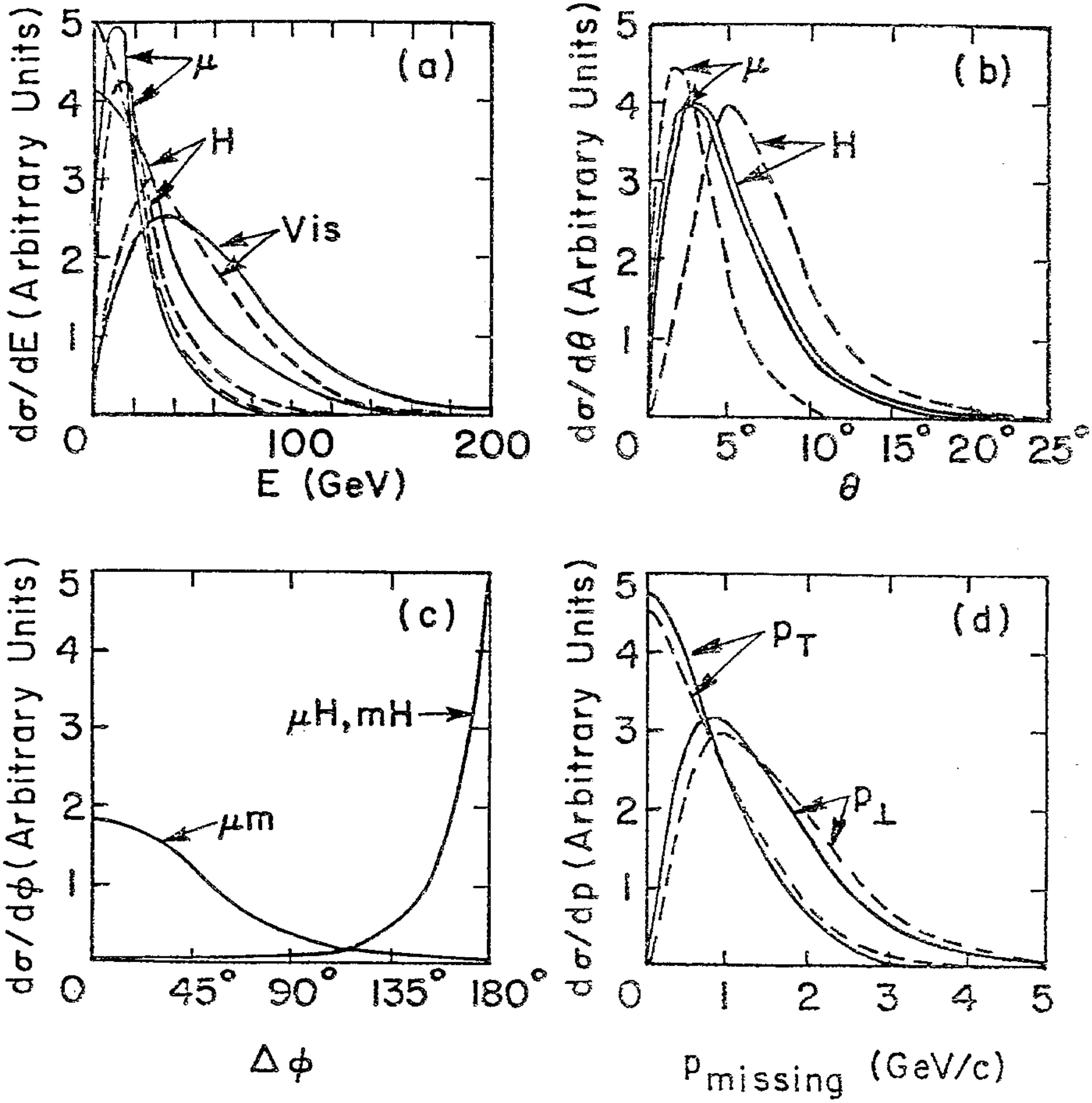

Fig. 2. Distributions in (a) energies, (b) polar angles relative to the beam direction, (c) azimuthal opening angles in a plane perpendicular to the beam, and (d) missing momentum perpendicular to the beam direction and transverse to the apparent production plane shown as solid curves for the chain reaction $\nu_\tau + N \to \tau^- + X$, $\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu$ with cuts $E_\mu > 4$ GeV, $E_H \geq 5$GeV. The dashed curves refer to the corresponding $\bar{\nu}_\tau$ reaction.

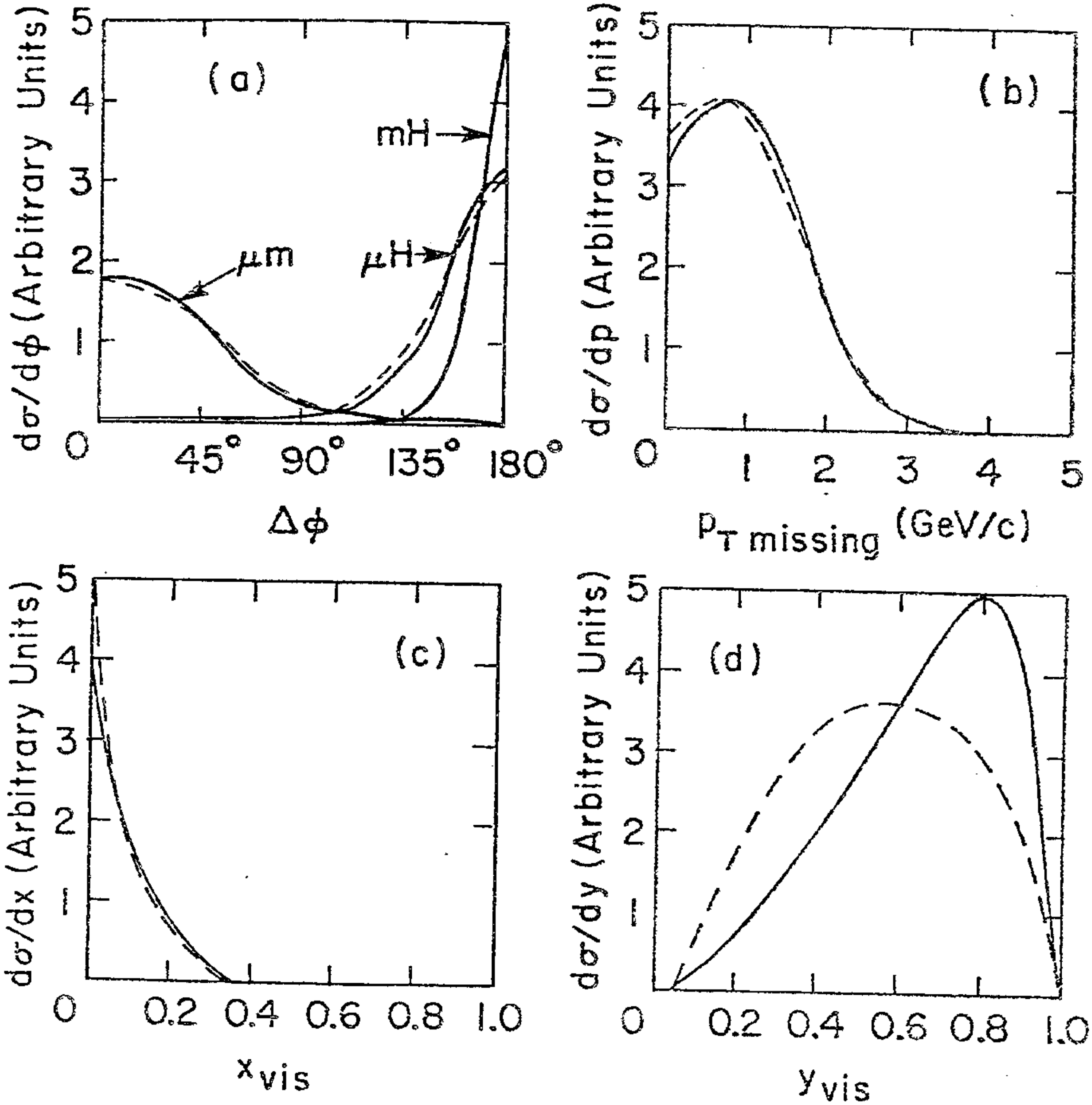

Fig. 3. Distributions for the $\nu_\tau \to \tau^- \to \mu^-$ (solid curves) and $\bar{\nu}_\tau \to \tau^+ \to \mu^+$ (dashed curves) reactions with cuts $E_\mu > 4$ GeV, $E_H > 5$ GeV and $(p_\perp)_{missing} > 1$ GeV/c.

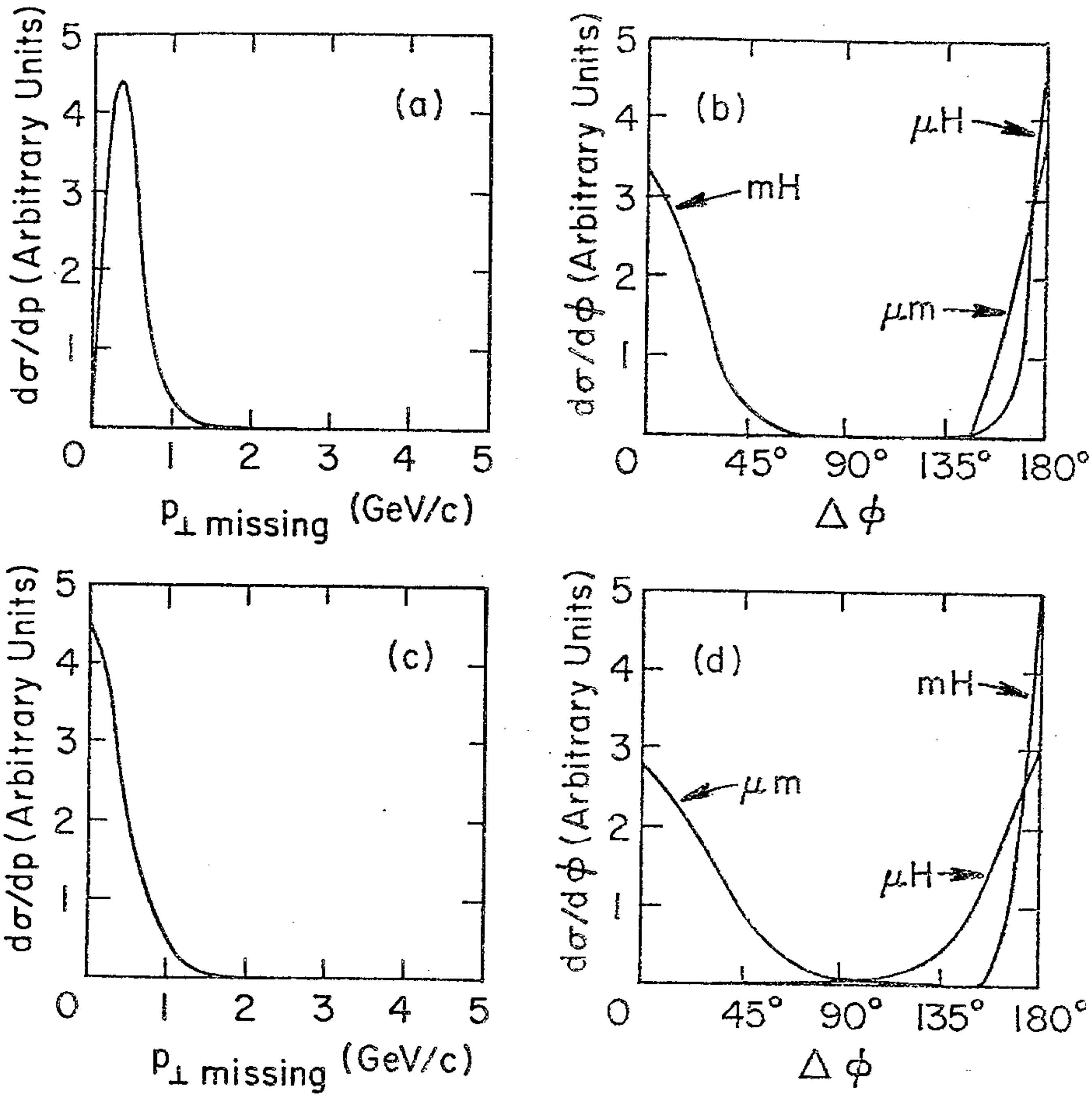

Fig. 4. Distributions for the background reaction $\nu_\mu+N\to\mu^-+X_c$, $X_c\to x+\nu_e+e^+$ in (a) missing momentum perpendicular to the beam direction with the cuts $E_\mu>4$ GeV, $E_H>5$ GeV and (b) the azimuthal opening angles with the additional cut $(p_\perp)_{missing}>1$ GeV/c. Similar distributions are given for the background reaction $\bar{\nu}_e+N\to e^++X_c$, $X_c\to x+\bar{\nu}_\mu+\mu^-$ in (c) and (d). In all cases, the electron is misinterpreted to be part of the hadron shower.